ISSN: 0975 – 9808
IJINN (2013), 4(1):1-7

Fluid dynamics in ejector-induced efficient slurry bubble column

Mekala Sivaiah and Subrata Kumar Majumder

Department of Chemical Engineering, Indian Institute of Technology, Guwahati, Assam, INDIA

skmaju@iitg.ernet.in, m.sivaiah@iitg.ernet.in

ABSTRACT:
In the present study the effects of operating variables such as slurry concentration, superficial slurry velocity, and superficial gas velocity and glycerol concentration on pressure drop and gas holdup are investigated in an ejector-induced slurry bubble column. Pressure drop is analyzed by Nicklin's model. To predict the gas holdup and pressure drop correlations have been developed as function of different dimensionless groups by introducing the operating variables and physical properties of the system in the gas-liquid-solid downflow slurry bubble column. From the experimental results it is observed that the higher gas holdup is obtained at lower slurry concentration due to lower resistance experienced by the gas bubbles to move downward.

Key words: Gas holdup, Pressure drop, Downflow, Bubble column, Slurry, Bubbles

INTRODUCTION

Gas-liquid-solid three-phase operations in column reactors have recently emerged to be very promising technologies for multiphase operations. These three-phase reactors are gaining importance as a simple and inexpensive means of achieving yields of chemical and biochemical processes like biological wastewater treatment, flue gas desulphurization, Fischer–Tropsch synthesis, methanol synthesis, dimethyl ether production, fermentation process and hydro treating of heavy petroleum residues. The advantages offered by these column reactors include: high liquid slurry phase content for the reaction to take place, higher residence time of gas bubbles, reasonable inter-phase mass transfer rates at low energy input, high selectivity and conversion per pass [1]. Also, there are low maintenance requirements due to simple construction and absence of any moving parts. It is not yet recommended for industrial applications due to lack of understanding of complex multiphase phenomena like holdup, pressure drop, mixing, and heat transfer phenomena in the downflow system. Three-phase pressure drop and holdup are essential elements for the design of process equipments which is the subject of numerous experimental and numerical studies. To design and control such equipment efficiently, the values of pressure drop and volumetric fractions of phases must be determined. In the present study the plunging liquid jet with ejector system is an efficient alternative in this context. Recently the importance of downflow plunging liquid jet column reactor in various chemical and biochemical industries are reported by various authors [2]-[10]. They reported that plunging jet reactors are finding increasing importance in a number of industrial applications. Based on the concept and advantages of plunging liquid jet as per literature, the present study earns an attention to research in this field. The present study can be useful for understanding the holdup characteristics and the models to predict the gas holdup and pressure drop for the development of three-phase reactor as well as further understanding of multiphase flow system.

EXPERIMENTAL PROCEDURE

Experiments were carried out in downflow plunging jet column reactor. The schematic diagram of a downflow column reactor is shown in elsewhere [11]. It consists of an ejector assembly (E), gas-liquid separator (SE), an extended pipeline contactor (C), and the other accessories which are mentioned in the legend. An extended pipeline contactor is provided below the ejector assembly for gas-liquid-solid three-phase downward flow. The separator was sufficiently large to minimize flooding of solid-liquid slurry inside the separator. The bottom outlet of the separator allows the liquid slurry to flow out while the top outlet allows the air to leave the separator. The liquid level inside the separator is controlled by operating the valves. For a particular flow through the nozzle, when the jet plunges into a liquid in the column, the secondary air is entrained through the hole provided beside the nozzle and three-phase mixing will be takes place in the mixing zone. A level of liquid-solid slurry is maintained at a particular height in the column by adjusting the solenoid valves. When the system attained steady state condition, the total height of the gas-liquid-solid mixing in the column (h_m), Slurry flow rate (Q_{sl}), and axial column pressure (ΔP) are noted. The overall gas holdup (ε_g) is estimated by the phase isolating method from the gas-liquid-mixing height (h_m) and clear slurry height (h_{sl}) in the column as

$$\varepsilon_g = \frac{h_m - h_l}{h_m} \quad (1)$$

Physical properties of the system

In the present study aqueous slurry of hydrophilic neutral Aluminum oxide is used for the experiment. Atmospheric air is used as gas phase. Effective viscosities of the slurry with different concentrations of glycerol are measured by viscometer (Model: Haake Rheostress 1, Thermo Electron Co., Germany). The average size of the particles is taken 96 μm which is measured by laser particle size analyzer (Malvern Instruments Ltd, Malvern, UK). The densities of the

system are measured by specific gravity bottle and the Surface tension of the liquid-solid slurry is measured by Tensiometer (Model: K9-Mk1, KRUSS GmbH Co., Germany). The physical properties of the different slurry concentrations (0.1 to 1.0 wt %) at an operating temperature of 25±1ºC are shown in Table 1.

Table 1: Physical properties of the liquid-solid slurry measured at 25 ± 1ºC

System	Slurry concentration (wt %)	Slurry density (kg/m³)	Viscosity*×10³ (kg/m.s)	Surface Tension** (N/m) ×10³
Glycerin A(0.5wt%)-solid slurry	0.1	998.10	1.820	64.8
	0.3	998.22	1.837	64.5
	0.5	998.35	1.877	63.9
	1.0	998.64	1.907	62.6
Glycerin B(1.0wt%)-solid slurry	0.1	999.14	1.832	66.3
	0.3	999.26	1.848	64.6
	0.5	999.37	1.883	64.3
	1.0	999.67	1.956	63.5
Glycerin C (1.5wt%) - solid slurry	0.1	1000.16	1.860	67.8
	0.3	1000.28	1.915	65.8
	0.5	1000.40	1.946	64.9
	1.0	1000.69	2.026	64.1
Water	-	997.05	1.528	74.0
Air	-	1.18	0.018	-

* Measured by Viscometer (Model: Haake Rheostress 1, Thermo Electron Co., Germany)

** Measured by Tensiometer (Model: K9-Mk1, KRUSS GmbH Co., Germany)

Theoretical background of pressure drop analysis

In the present study of vertical downflow of a mixture consisting of gas as dispersed phase in the form of bubbles, liquid as continuous phase and the solids in the form of fine spherical particles, the total pressure drop is measured at the bottom of the column due to the weight of liquid-solid slurry inside the column. The measured total pressure drop is analyzed by Nicklin's model. By the energy balance the total pressure drop (ΔP_t) can be written as

$$\Delta P_t = \Delta P_r + \Delta P_i \qquad (2)$$

where, ΔP_r is the reversible pressure drop due to reversible work done in lifting the gas-liquid-solid mixture and it depends on the input volumetric flow rates of the gas, liquid and solid. ΔP_i is the irreversible pressure drop. It is equal to the energy loss in heat due to relative motion between the phases of gas-liquid-solid and the wall friction. The reversible pressure drop (ΔP_r) and the irreversible pressure drop (ΔP_i) can be calculated as [12]

$$\Delta P_r = \varepsilon_l \rho_l g h_m + \varepsilon_g \rho_g g h_m \qquad (3)$$

$$\Delta P_i = \Delta P_s + \Delta P_w \qquad (4)$$

where, ΔP_w is the pressure drop due to wall shear and ΔP_s is the pressure drop due to slip between liquid-solid and gas phase. Pressure drop due to slip is calculated as [12]

$$\Delta P_s = (1-\varepsilon_g)\rho_l g h_m + \varepsilon_g \rho_g g h_m - \left(Q_{sl}\rho_l g h_m / Q_{sl} + Q_g\right) - \left(Q_g \rho_g g h_m / Q_{sl} + Q_g\right) \qquad (5)$$

By substituting Eq. (4) in (2) one gets:

$$\Delta P_t = \Delta P_r + \Delta P_s + \Delta P_w \qquad (6)$$

Substituting for ΔP_r from Eq. (3) and for ΔP_s from Eq. (5) in Eq. (6) the pressure drop due to wall friction (ΔP_w) can be expressed as

$$\Delta P_w = \Delta P_t - 2(1-\varepsilon_g)\rho_l g h_m - 2\varepsilon_g \rho_g g h_m + \left(\frac{Q_{sl}\rho_l g h_m}{Q_{sl}+Q_g}\right) + \left(\frac{Q_g \rho_g g h_m}{Q_{sl}+Q_g}\right) \qquad (7)$$

RESULTS AND DISCUSSION

Effect of different variables on gas holdup

The effect of superficial slurry velocity, gas velocity and glycerol concentration (GA) on gas holdup is shown in the Fig. 1. It is observed that on increasing the slurry velocity and gas velocity the gas holdup is increased. As the slurry flow rate increases, the kinetic energy of the liquid jet entrains more gas into the liquid in the column which results in increase of gas holdup. Also increase in the gas or liquid velocity in the column leads to increase the mixing of gas-liquid-solid mixture because of increase in the intensity of the momentum of mixture thereby increases the bubble formation which enhances to increase the gas holdup. From the Fig. 1 it can be seen that the gas holdup is increased with increase in glycerol concentration. In the present study the range of liquid viscosity is less than 3 mPa.s, so the gas holdup is increased with glycerol concentration due to the formation of uniform bubbly layers in the column as reported by many authors [13]-[15].

Prediction of gas holdup

In the present study within the range of system variables examined the gas holdup is depend on the slurry velocity (u_{sl}), gas velocity (u_g), column diameter (d_c), particle diameter (d_p), slurry density (ρ_{sl}), slurry viscosity (μ_{sl}), and surface tension of the liquid (σ_l). Hence an attempt has been made to correlate the gas holdup (ε_g) by the dimensional analysis with these variables. The gas holdup (ε_g) as a function all these variables can be written as

$$\varepsilon_g = f(u_{sl}, u_g, \mu_{sl}, \rho_{sl}, d_c, h_m, d_p, \sigma_l, g) \qquad (8)$$

The correlation is developed by multiple regression analysis which is expressed by the Eq. (9) with the correlation coefficient of 0.987 and standard error of 0.098. The comparison of experimental values and predicted values of overall gas holdup (Eq. (9)) is shown in Fig. 2.

$$\varepsilon_g = 1.05\times10^{-6}\left(\frac{u_{sl}}{u_g}\right)^{-0.118}\left(\frac{d_c u_{sl}\rho_{sl}}{\mu_{sl}}\right)^{2.211}\left(\frac{u_{sl}^2}{g d_c}\right)^{-0.104}\left(\frac{h_m}{d_p}\right)^{-0.519} \qquad (9)$$

Effect of different variables on total pressure drop

The effect of slurry velocity and slurry concentration on total pressure drop is shown in Fig. 3. It is seen that

the total pressure drop is decreased with increase in slurry velocity and increased with increase in slurry concentration. Increase in slurry flow rate the gas holdup is increased (Fig. 1). As the gas holdup increases the total pressure drop is decreased due to increase the apparent difference in density. Addition of the solids to the liquid increases the average density of the slurry inside the column since the density of the column contents is increased which contributed to increase the total pressure drop.

Effect of different variables on pressure drop due to wall shear

The effect of slurry velocity and slurry concentration on pressure drop due to wall shear is shown in Fig. 4. The pressure drop due to wall shear is increased with increase in slurry velocity and it decreased with increase in slurry concentration. This is due the reason that with increase in slurry velocity as the fast moving liquid at the central core of the column the bubbles try to migrate towards the wall and increase the friction at the wall. Thus the variation in pressure drop due to wall shear is more at higher slurry flow rates compared to lower slurry flow rates because of large difference in the gas holdup profiles. Increase in solid concentration the apparent viscosity of the slurry increases which enhance to decrease the liquid-solid circulation in the column and decrease the pressure drop due to wall friction. The effect of gas holdup on pressure drop due to wall friction is shown in Fig. 5. As the gas holdup increases the interaction between liquid-bubble and the liquid-solid-wall interface increases which results in increase in pressure drop due to wall friction. From Fig. 5 it is also observed that the pressure drop due to wall friction is not only a function gas holdup but also a function of slurry concentration.

From Fig. 5 a general functional relationship between pressure drop due to wall friction and gas holdup is developed as

$$\Delta P_w = a\varepsilon_g + b \qquad (10)$$

where

$$a = 9.59\times10^3 w^2 - 14.94\times10^3 w + 24.19\times10^3 \qquad (11)$$

$$b = -4.64\times10^3 w^2 + 5.99\times10^3 w - 5.52\times10^3 \qquad (12)$$

In the present downflow study the values of pressure drop due to wall friction may be positive or negative. This means the total pressure drop may be less than the weight of the column contents because of slip in local down flows of the liquid [12]. In the Fig. 5 the point of intersection between Y-axis (ΔP_w profile) and X-axis (ε_g profile) is the critical gas holdup. The gas holdup at which the pressure drop value is zero can be represented as critical gas holdup ($\varepsilon_{g,c}$) which can be expressed by the Eq. (13) from the Eq. (10).

$$\varepsilon_{g,c} = -b/a \qquad (13)$$

The variation of critical gas holdup ($\varepsilon_{g,c}$) and the constants (a, b) with slurry concentration is shown in Fig. 6. It is observed that the critical gas holdup values are decreased with increase in slurry concentration due to the increase in apparent viscosity with the slurry concentration. The value of critical gas holdup for solid (Al_2O_3)-glycerol-air system at slurry concentration w = 0.1% is 0.221 whereas at slurry concentration w =1.0% is 0.196.

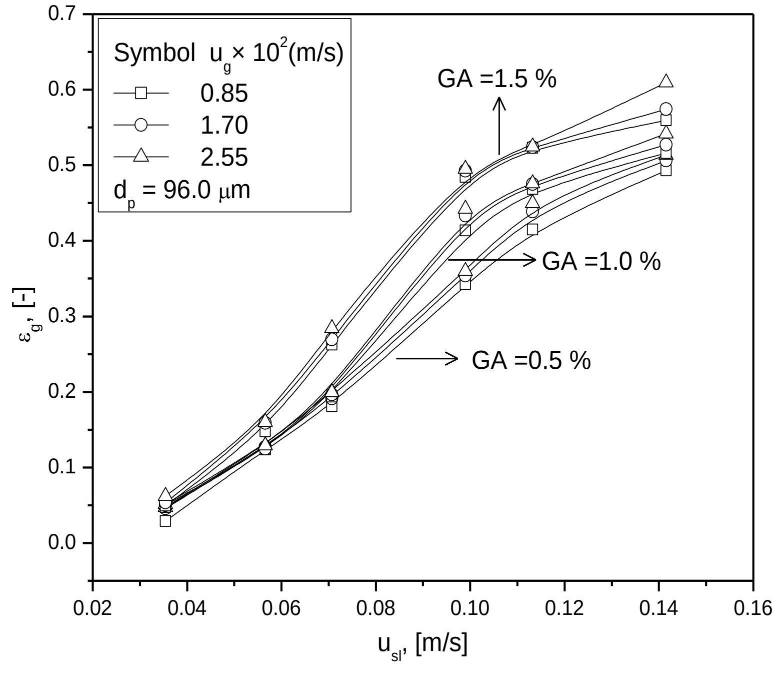

Fig. 1: Effect of slurry velocity, gas velocity and glycerol concentration on gas holdup

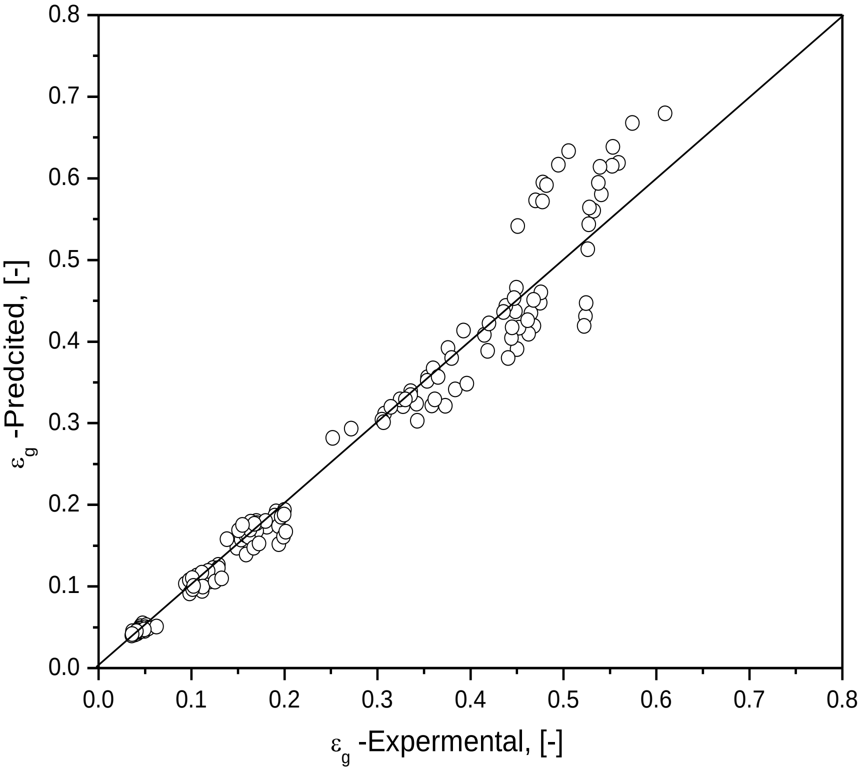

Fig. 2: Parity of experimental and predicted values of gas holdup

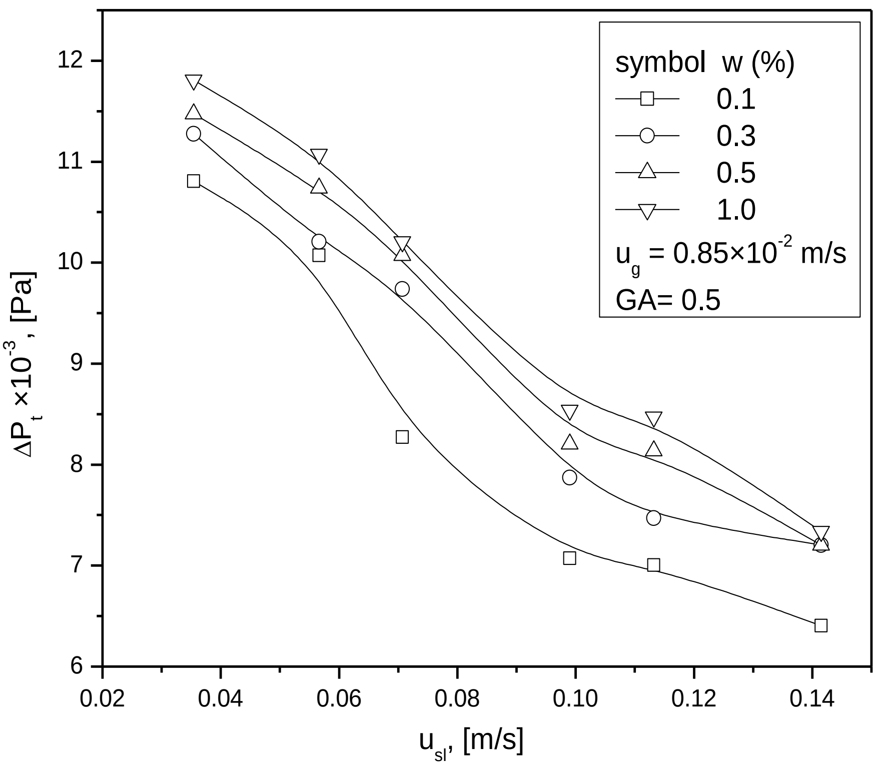

Fig. 3: Effect of slurry velocity, slurry concentration on total pressure drop

ISSN: 0975 – 9808
IJINN (2013), 4(1):1-7

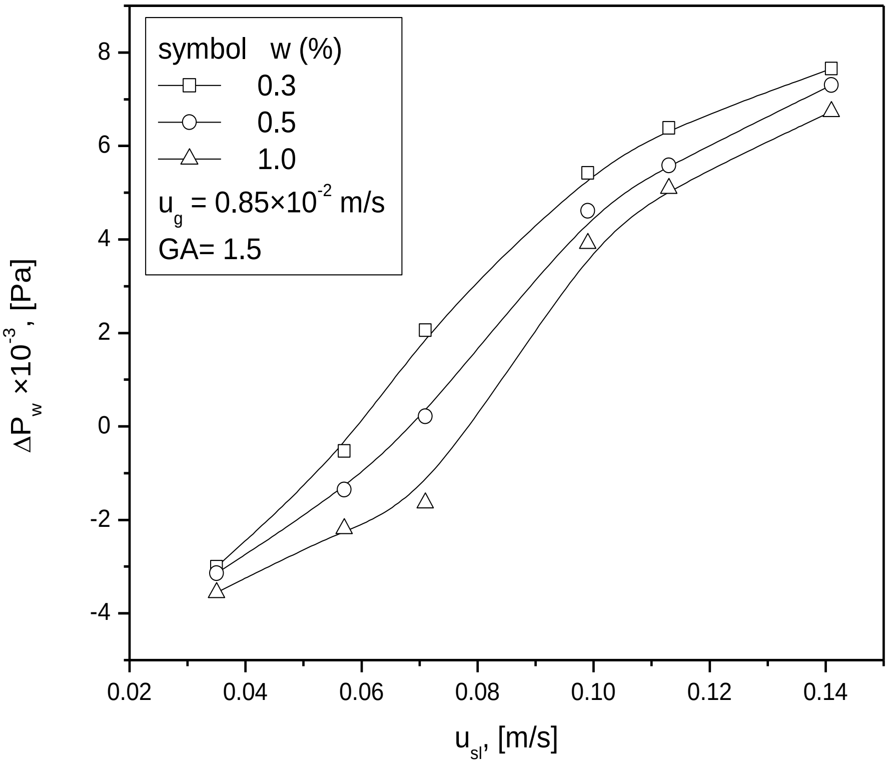

Fig. 4: Effect of slurry velocity and slurry concentration on pressure drop due to wall friction

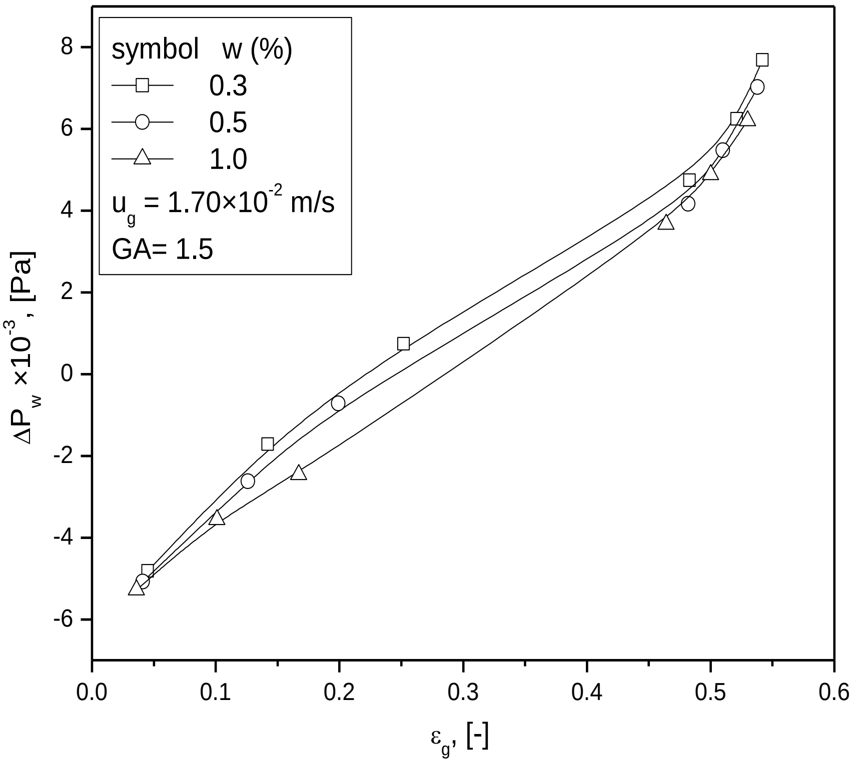

Fig. 5: Variation of pressure drop due to wall friction with gas holdup (ε_g)

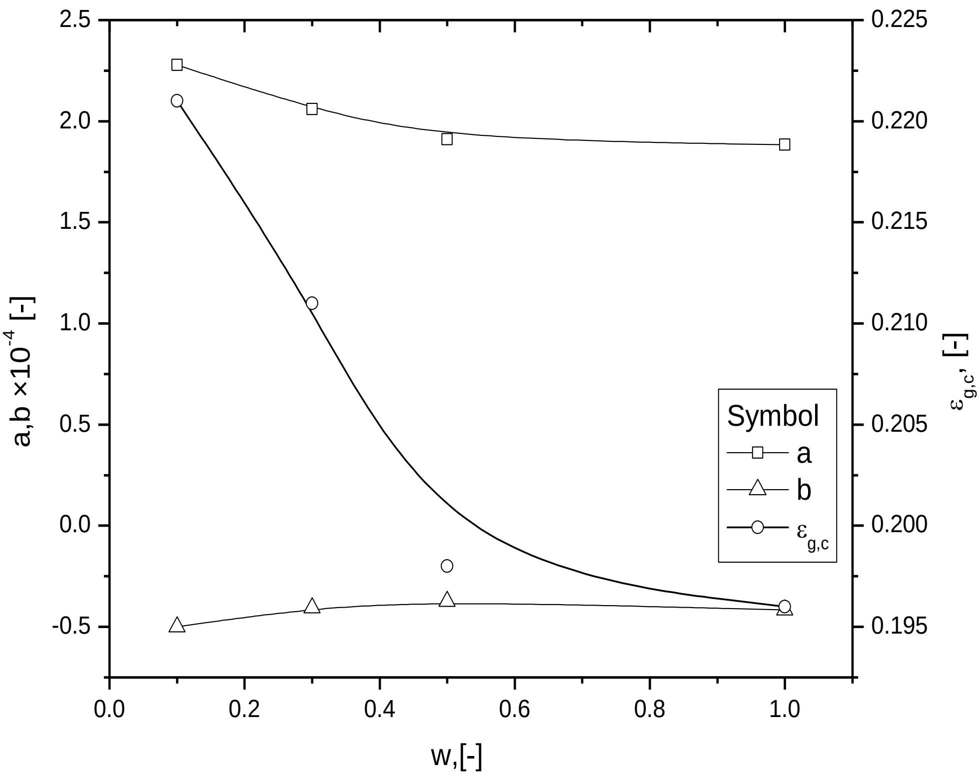

Fig. 6: Variation of a, b, and $\varepsilon_{g,c}$ with slurry concentration

CONCLUSION

In the present work, the gas holdup and pressure drop of gas-liquid-solid downflow system are experimentally investigated in a downflow slurry bubble column. The pressure drop and gas holdup are strongly dependent on the motive fluid flow rate and system properties. From the present experimental study it is observed that the total pressure drop is decreased with increase in slurry flow rate and increased with slurry concentration. The total pressure drop is analyzed by Nicklin's model. The correlation developed for pressure drop due to wall shear is good in agreement with the experimental results. The gas holdup is increased with increase in superficial gas and slurry velocities and decreased with increase in slurry concentration. A generalized correlation has been developed for gas holdup as a function of various dimensionless groups comprising of different operating variables. This study may be a useful tool for the possible scale up of three-phase column for different chemical processes.

NOMENCLATURE

a	Parameter used in Eq. (10), [-]
b	Parameter used in Eq. (10), [-]
d_c	Column diameter, [m]
h_m	Gas-liquid-solid mixing height, [m]
ρ_{sl}	Density of liquid-solid slurry, [kg/m^3]
ρ_g	Density of gas, [kg/m^3]
g	Acceleration due to gravity, [m/s^2]
Q_g	Volumetric flow rate of gas, [kg/m^3]
Q_{sl}	Volumetric flow rate of slurry, [kg/m^3]
u_g	Gas superficial velocity, [m/s]
u_{sl}	Slurry superficial velocity, [m/s]
ΔP_t	Total pressure drop, [Pa]
ΔP_r	Reversible pressure drop, [Pa]
ΔP_i	Irreversible pressure drop, [Pa]
ΔP_s	Pressure drop due to slip, [Pa]
ΔP_w	Pressure drop due to wall friction, [Pa]
w	Slurry Concentration, [wt%]
ε_g	Gas hold up, [-]
$\varepsilon_{g,c}$	Critical gas hold up, [-]
μ_{sl}	Slurry Viscosity, [Ns/m^2]

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